

Practical Implementation of the Two-Measurement Correction Method in Automotive Wind Tunnels

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ABSTRACT

In recent years, there has been renewed attention focused on open jet correction methods, in particular on the two-measurement method of E. Mercker, K. Cooper, and co-workers. This method accounts for blockage and static pressure gradient effects in automotive wind tunnels and has been shown by both computations and experiments to appropriately adjust drag coefficients towards an on-road condition, thus allowing results from different wind tunnels to be compared on a more equitable basis. However, most wind tunnels have yet to adopt the method as standard practice due to difficulties in practical application. In particular, it is necessary to measure the aerodynamic forces on every vehicle configuration in two different static pressure gradients to capture that portion of the correction.

Building on earlier proof-of-concept work, this paper demonstrates a practical method for implementing the two-measurement procedure and demonstrates how it can be used for production testing. The approach requires a correlation of multiple vehicle shapes measured in two different static pressure gradients. For vehicles subsequently tested, the correlation can be used in place of the second measurement so that there is no impact to productivity in the wind tunnel operation. This correlation approach has been applied to both the full-scale and model-scale wind tunnels at Chrysler. The results presented show that this approach is quite accurate (although naturally depending on the vehicles selected for the correlation) and is suitable for day-to-day development testing. In addition, the agreement in results between these two wind tunnels is shown to improve considerably with application of the correction.

CITATION: Lounsberry, T. and Walter, J., "Practical Implementation of the Two-Measurement Correction Method in Automotive Wind Tunnels," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(2):2015, doi:10.4271/2015-01-1530.

INTRODUCTION

Chrysler uses both 3/8 scale model and full scale wind tunnels for aerodynamic development. It is important to have good correlation between tools to accurately predict whether a program is meeting its aerodynamic targets for fuel economy and other purposes.

The Chrysler Aerodynamics Model Test Facility (AMTF) was built in the early 1990's [1] as a pilot for what was planned to be a full scale aerodynamic and climatic wind tunnel. The 3/8 scale model wind tunnel originally went into production with a slotted wall test section. The Chrysler full scale Aeroacoustic Wind Tunnel (AAWT) was completed in 2002 [2]. Between the times the AMTF was conceived in the late 1980s and the AAWT was conceived in the late 1990s, consumer tastes changed and as a result, the design of automotive wind tunnels transformed significantly. The trend in the U.S. towards larger vehicles (by sales volume) led to larger wind tunnels being built. In addition, low interior cabin noise levels had become a consumer priority. Thus, the AAWT was designed as a semi-open jet aeroacoustic facility and not as a "scaled up" version of the AMTF as had originally been planned.

After the full scale AAWT opened, the central portion of the slotted wall section in the AMTF was removed. This effectively turned it into an open jet wind tunnel, with the goal of improving the geometric similarity to the AAWT. Although the results from the scale model facility in open jet configuration were always lower than the full scale vehicle results, it was felt that for most production development this difference was reasonably predictable and suitable "adjustment factors" were used to compensate for the differences in aero drag (within a few percent) and lift.

However, as the demand to meet fuel economy requirements increased it became even more critical for the aerodynamics performance during early development to be accurately predicted. It was no longer acceptable to be "within a few percent" on predicting aerodynamic status. To support fuel economy efforts, the confidence in meeting program targets had to be very high and significant "fudge factors" were unacceptable. Something had to be done to eliminate or reduce these.

The physical differences in the two wind tunnels contributed in large part to the measurement differences seen. A project was undertaken to make physical changes to the AMTF to further improve its similarity to the AAWT, and to investigate correction methods for both wind tunnels, the latter of which is the main topic of this paper.

The current state-of-the-art approach for automotive wind tunnel boundary corrections was developed by Mercker and Cooper [3], building on the earlier work of Mercker, Wiedemann, and co-workers [4,5,6]. These works provide methods to correct both for interference effects (e.g., nozzle and collector blockage) as well as pressure gradient (horizontal buoyancy and wake distortion) effects. An operational disadvantage of the Mercker-Cooper approach is that two separate measurements are required to arrive at the corrected result, one in the wind tunnel's normal pressure field, and another in a second, artificially-imposed pressure field. Walter et al. [7] demonstrated the feasibility of replacing the second measurement with a prediction based on a one-time correlation of multiple vehicles. They showed that the corrected drag coefficient could be predicted with good confidence, so that only a single measurement is needed in day-to-day testing.

The objectives of this paper are to demonstrate application of the Walter et al. [7] correlation approach to Chrysler's two wind tunnels, provide practical guidance for implementing the two-measurement correction method, and to compare the results obtained after the correction.

The following section provides a summary of the Mercker-Cooper [3] two-measurement method, including the practical steps that should be considered to ensure data quality. The measurement details and correlation results for both facilities are then described, followed by a comparison of the results between the two wind tunnels.

THE TWO-MEASUREMENT CORRECTION METHOD

Summary of the Method

Mercker and Cooper [3] provide a detailed description and validation of the two-measurement procedure. In practical implementation, the procedure is simply the solution of the following two equations:

$$C_{Dc} = \frac{C_{D1m} + [C_{p1m}(x_{sens}) - C_{p1m}(x_{frt})]}{q_c/q_m}$$

$$= \frac{C_{D2m} + [C_{p2m}(x_{sens}) - C_{p2m}(x_{frt})]}{q_c/q_m} \quad (1)$$

In these equations, the coefficients with the subscript m are measured quantities: C_{Dm} is the measured drag coefficient with no corrections, and C_{pm} is the empty-tunnel pressure coefficient. The subscripts 1 and 2 refer to measurements in two different longitudinal pressure

distributions, the normal pressure distribution and a second artificially imposed one. All other conditions of the two measurements (vehicle configuration, test speed, etc.) are identical. The subscript c refers to corrected quantities. Procedures to apply the blockage corrections (i.e., calculate q_c as a function of q_m , vehicle geometry, and wind tunnel geometry) are succinctly summarized by Walter et al. [8]. The approach summarized there, which was developed by Mercker et al. [3, 4], requires the simultaneous measurement of dynamic pressure using both the nozzle method and the plenum method.

$C_p(x_{frt})$ in Eqs. (1) refers to the empty-tunnel pressure coefficient at the front bumper of the model, and $C_p(x_{sens})$ refers to the empty-tunnel pressure coefficient at the (yet to be determined) wake sensitivity location. As discussed in the references [3,4,8], the wake sensitivity length is related to the distortion of the wake and its effect on the vehicle's flow field. Each in-plane integral parameter (C_D , C_L , C_{PM}), as well as each local pressure coefficient, has a distinct sensitivity length.

Eqs. (1) provide two equations and two unknowns. The unknowns are the corrected drag coefficient, C_{Dc} , and the wake sensitivity length, x_{sens} , which by convention is measured from the nozzle exit plane. The solution to Eqs. (1) can be broken into two steps:

$$C_{Dw} = C_{D1m} + [C_{p1m}(x_{sens}) - C_{p1m}(x_{frt})]$$

$$= C_{D2m} + [C_{p2m}(x_{sens}) - C_{p2m}(x_{frt})] \quad (2a)$$

and

$$C_{Dc} = \frac{C_{Dw}}{q_c/q_m} \quad (2b)$$

The right hand side of Eq. (2a) is the same as the numerator in Eq. (1). C_{Dw} is the portion of the correction attributable to buoyancy and wake distortion, but does not include the blockage (dynamic pressure) correction, which is included with Eq. (2b) in the second step.

Figure 1 shows an example of the graphical solution of Eqs. (2a). The wake sensitivity length, x_{sens} , is treated as a free parameter and trial values of C_{Dw} , C_{D1t} and C_{D2t} are calculated until the correct C_{Dw} is determined by the intersection of the two curves. The far left side of each curve represents the original measured results from the wind tunnel in each of the gradients, because $x = x_{frt}$, so the ΔC_p terms in Eqs. (2a) are zero. In this example, the two measured drag coefficients were about 0.341 and 0.351 in each gradient, and the result corrected for buoyancy and wake distortion is about $C_{Dw} = 0.347$. The Appendix provides a general step-by-step calculation procedure using this example.

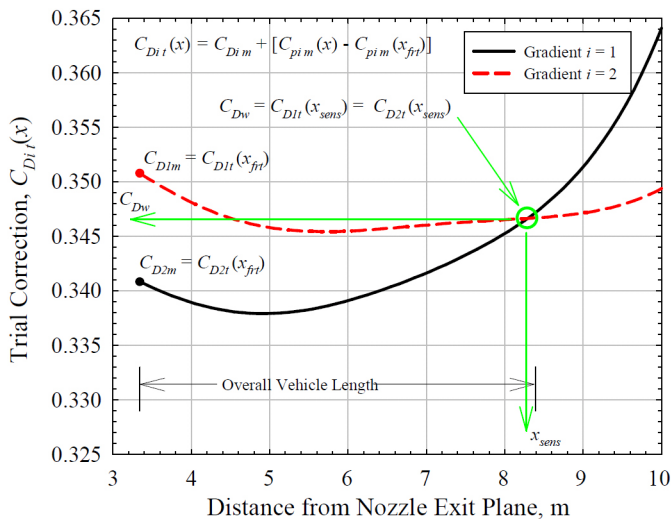


Figure 1. Example graphical solution for the two-measurement method

Practical Considerations

The first step in developing the needed correlation approach is to perform actual two-gradient measurements to develop a database of various vehicle types and sizes. The sample of vehicles selected should represent the range of vehicle shapes and sizes that are likely to be tested in the wind tunnel in the future. Ideally, at least 25-30 individual vehicle configurations and test conditions (e.g., different yaw angles) appear appropriate to cover the range of drag coefficients needed to formulate a linear regression of wake distortion effects.

In both wind tunnels, the second gradients were produced by using a “ramp” that was placed at the wind tunnel collector entrance. Further detail is provided later in the paper. This approach is similar to previous work [8,9] and was selected primarily for its ease of implementation. Detailed dimensions of the gradient ramp are available from the authors. From a practical standpoint, however, the pressure gradient corrections appear to be quite insensitive to precisely how the second pressure gradient is generated [3,7,10,11].

A key point is to generate a second gradient without affecting the wind tunnel's calibrated static pressure (usually at the center of turn table rotation), as the dynamic pressure calibration would then be invalidated. If the static pressure is affected by generating the second gradient then it is necessary to recalibrate the dynamic pressure under the new gradient condition or develop a correction for the modified static pressure at the calibration location.

Although not covered in this paper, another important aspect is to ensure that both methods for open jet dynamic pressure (nozzle method and plenum method) can be measured simultaneously. It is possible to perform single measurements and build a database using only one transducer and manually switching between the two q methods, but this would not work in practical implementation for production development testing.

These are important steps that are sometimes not given proper attention, but the final data corrections are only as good as the inputs that are entered. Building a good quality database is critical to using this method to produce accurate results.

In this paper, the corrections are demonstrated only for the drag coefficient. Lift results were checked and corrections were deemed to be insignificant and thus not performed. In the results presented below, focus is on the pressure gradient corrections (horizontal buoyancy and wake distortion). However, blockage corrections accordingly [8] have been applied to all of the data.

3/8 SCALE MODEL WIND TUNNEL (AMTF)

The Chrysler 3/8 scale model wind tunnel has been in use for production development for over twenty years. However, as the full scale Aero Acoustic Wind Tunnel came online in 2002, it was observed that there were some differences in the results between the two wind tunnels. The differences were a result of primarily wind tunnel differences but also some model issues; this paper focuses only on the wind tunnel aspects.

The main objective was to make the AMTF more like the full scale wind tunnel, where possible. As the full scale wind tunnel was considered more state-of-the-art, with a two-stage boundary layer system and relatively low static pressure gradient in the test section, it was considered that getting the AMTF layout closer to the full scale tunnel would result in more consistent and predictable results. This would in turn provide more confidence in both the aerodynamic increments as well as absolute magnitudes and thus better predictive capabilities for on-road performance.

Shortly after the full scale AAWT opened, the central portion of the slotted wall section in the AMTF was permanently removed, as shown in Figure 2. The downstream slats took the place of a traditional collector, and indeed appeared to mitigate the pressure pulsations normally associated with open jet test sections. Subsequently, an upgrade to the 3/8 wind tunnel floor and boundary layer system was completed in early 2013, in which the test section floor and turntable were replaced with an extremely flat and flush floor. Also, a tangential blowing slot was added downstream of the existing suction scoop to improve boundary layer profile and further improve the similarity to the full scale wind tunnel.



Figure 2. Chrysler 3/8 scale model wind tunnel after upgrades

The 3/8 scale model wind tunnel has relatively higher blockage ratios than the full scale tunnel, and the models sit slightly closer to the nozzle exit. Also, it was found during the preparations for the upgrade that there was a more substantial static pressure gradient due to collector interference effects. Thus, it would be important to account for these nozzle blockage and pressure gradient effects to produce results comparable to the full scale wind tunnel.

Below is some basic information and key attributes of the 3/8 scale model wind tunnel for reference:

- Semi-open jet test section (rear slotted section for collector)
- Two-stage boundary layer system (suction scoop + tangential blowing slot)
- Primary dynamic pressure setting = Plenum method

Table 1. Specifications of 3/8 scale model wind tunnel

	Actual dimension	Full scale equiv.
Nozzle size	3.11 sq. m	22.1 sq. m
Turntable center from NEP	1.832 m	4.88 m
Test section length (to rear slotted section)	4.75 m	12.6 m
Boundary layer thickness (at x-937)	7 mm	19 mm
Displacement thickness	0.25 mm	0.7 mm

As part of the upgrade and objective to make the wind tunnel produce comparable results to full scale, preparations were made to implement the two-measurement method (in both facilities) and to start the new data correction method at the completion of the scale tunnel upgrade so that all changes would be made simultaneously.

Measuring Normal and Second Static Pressure Distributions

To induce a second static pressure gradient, a scaled down version of the ramp was used in the full scale wind tunnel was used and was set at the same (scaled) distance from nozzle exit as for the full scale testing.

The empty tunnel static pressure distributions were measured using a Pitot-static probe on mounted on a 254 mm tall stand that could be moved along axially, with care to ensure that an adequate spacing was used to properly resolve the gradient. Again, this is a critical step for calculating the corrected results via two-measurement method, and it is extremely important to make sure that accurate empty-tunnel pressure measurements are made.

As the distributions were smooth due to lack of perturbations in the floor, a sixth order curve fit was used to estimate the gradient between axial points. This is useful for the iterative process of calculating the wake sensitivity length.

A graph of both static pressure distributions in the empty tunnel is shown in Figure 3.

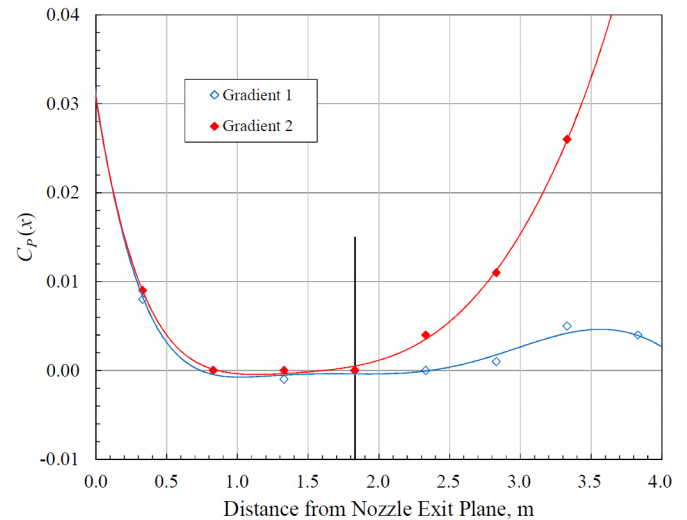


Figure 3. AMTF, normal and second static pressure distributions. Turn table center is shown as the vertical line at X = 1.83 m.

Building a Database for Wake Distortion Estimation

Once the setup work is performed, then the task of measuring a variety of different models of different shapes and sizes, with several configurations for each, is performed.

In this case, a database was built using the following models (Table 2), all tested at 207 km/h, or about 78 km/h full scale:

- 7 different models of various shapes and sizes
- 25 data points (including yaw)
- Frontal areas from 2.29 sq. m to 3.41 sq. m (blockage ratios from 10.4% to 15.4%)

Table 2. 3/8ths scale models used to build database

Model	Blockage ratio	Configurations
Small sedan	10.4%	Baseline 0, 9 deg; taped grille, wheel covers
Midsize sedan	10.5%	Baseline 0, 9 deg.
Large sedan	10.8%	Baseline 0, 9 deg; spoiler, bellypans, taped grille
Midsize SUV	12.8%	Baseline 0, 9 deg; spoiler, taped grille, wheel covers
Large SUV	13.3%	Baseline 0, 21 deg; taped grille
Minivan	13.6%	Baseline 0, 9 deg; taped grille, airdam
Pickup truck	15.4%	Baseline 0, 9 deg.